

PUBLICATIONS BRANCH
SUBMARINE MEDICAL CENTER

FILE COPY NO. 2



Submarine Base, Groton, Conn.

REPORT NUMBER 498

VISION UNDERWATER

by

Paul R. Kent
CDR MSC, USN

Bureau of Medicine and Surgery, Navy Department
Research Work Unit MF011.99-9002.04

Approved and Released by:

C. L. Waite, CAPT MC USN
COMMANDING OFFICER
U.S. Naval Submarine Medical Center

11 July 1967

PUBLICATIONS BRANCH
SUBMARINE MEDICAL CENTER

FILE NO. 2



This document has been approved for public release and sale;

SUMMARY PAGE

THE PROBLEM

To compare visual resolution of a target, or set of targets, and size and distance judgments underwater, with the same measures in air, and also to investigate the visibility of fluorescent versus non-fluorescent paints used on such targets.

FINDINGS

At short range, visual resolution of a target in water was better than in air, but except for these short ranges, both size and distance were underestimated underwater when compared to air viewing. Fluorescent pigments were found to be more visible underwater than non-fluorescent types.

APPLICATIONS

The results of this investigation have direct application to the training and operational use of divers, and for those charged with the responsibility of production of underwater markers and signals.

ADMINISTRATIVE INFORMATION

This material was presented to the annual meeting of the American Academy of Optometry, Chicago, Illinois, 13 December 1965, and subsequently published in the American Journal of Optometry and Archives of American Academy of Optometry, Vol. 43, No. 9, September 1966. This reprint has been designated as SubMedResLab, SubMedCen Report No. 498 under date of 11 July 1967. It is Report No. 4 on BuMed Research Work Unit MF011.99-9002.

PUBLISHED BY THE NAVAL SUBMARINE MEDICAL CENTER

This document has been approved for public release and sale;
its distribution is unlimited.

AMERICAN JOURNAL OF OPTOMETRY
and ARCHIVES of
AMERICAN ACADEMY OF OPTOMETRY

Vol. 43

September, 1966

No. 9

VISION UNDERWATER*

Paul R. Kent†

U.S. Naval Submarine Medical Center
New London, Connecticut

This investigation began with the preparation of a questionnaire designed to determine the visual adaptation of a diver to his water environment. It was submitted to 100 U.S. Naval officer and enlisted divers trained in either, or both, SCUBA, Figure 1, and hard hat diving,

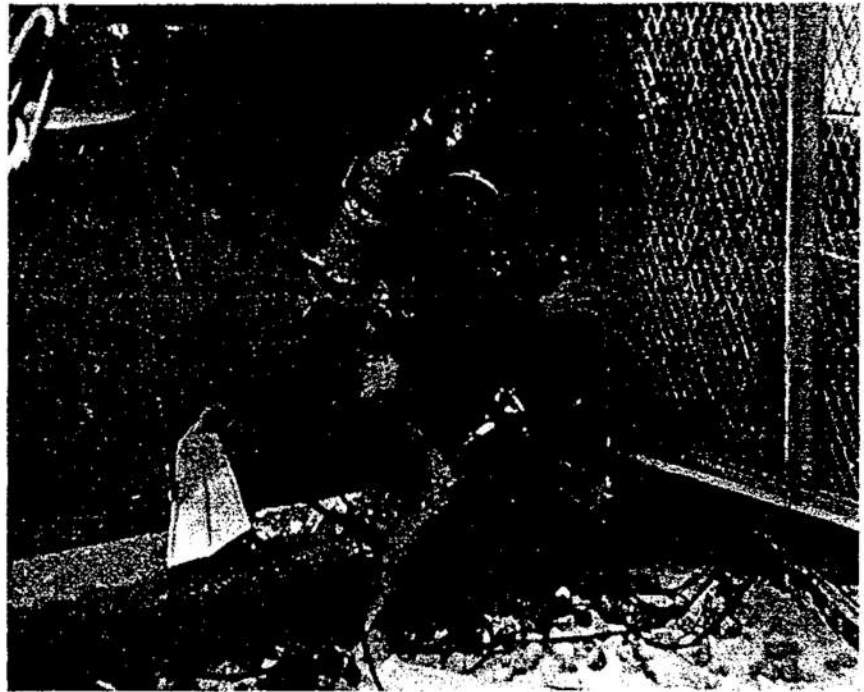


Fig. 1. SCUBA diving mask.

*Read before the annual meeting of the American Academy of Optometry, Chicago, Illinois, December 13, 1965. For publication in the September, 1966, issue of the AMERICAN JOURNAL OF OPTOMETRY AND ARCHIVES OF AMERICAN ACADEMY OF OPTOMETRY.

†Optometrist. M.Opt., Commander, Medical Service Corps, United States Navy. Fellow, American Academy of Optometry.



Fig. 2. Hard hat diving helmet.

Figure 2, of whom 92 responded. Basic questions were asked regarding visual acuity and depth perception at shallow depths in clear water.

The question regarding visual acuity was: Compare your ability to see underwater and on the surface. While underwater, do underwater objects within about 20 feet of you appear (a) less clear than on the surface, (b) clearer than on the surface, or (c) no different? Of the SCUBA divers, 50 per cent responded less clear, 11 per cent clearer, and 39 per cent no difference. For the hard hat divers it was 61 per cent less clear, 7 per cent clearer, and 32 per cent no difference.

Navy divers have no worse than 20/30 distance visual acuity each eye, correctable to 20/20. Only three of the divers reported that they wore glasses for distance. Two of these claimed to see poorer underwater and one better.

The SCUBA divers were asked two questions related to depth perception: (1) Do you think that your depth perception (or ability to judge the distance of objects away from you) is different underwater than on the surface? There were 78 per cent yes answers, 18 per cent

no, and 4 per cent not sure. The second question was: If your depth perception underwater seems different than on the surface, do you think that objects underwater appear (a) nearer to you, or (b) farther away? Ninety-four per cent responded closer and 6 per cent farther away. There was overwhelming agreement that objects appeared closer in the underwater environment, but less of a consensus regarding underwater visual acuity.

The next phase was an investigation of selected visual parameters under controlled conditions. This was accomplished by research groups from the Research Division of the Submarine Medical Center, Groton, Connecticut. One team, headed by Commander P. R. Kent, Research Optometrist, investigated visual resolution, or acuity, underwater¹. Another group, led by J. A. S. Kinney, Ph.D., investigated size and distance judgments and color vision in the water environment.

OBJECTIVE

The experiment was designed to compare visual resolution of a target, or set of targets, when viewed in air and underwater at the same physical distance. Since the testing distance was 16 feet, "normal" vision in air was 16/16.

APPARATUS AND METHOD

The investigation took place in the Escape Training Tank located at the U.S. Naval Submarine Base, New London/Groton, Connecticut. The tank is a large upright cylinder filled with water, 120 ft. deep by 18 ft. wide. The water is kept clear by constant recirculation through a filtering system, and is held at a temperature of 92° Fahrenheit. During testing all outside windows were covered and the lights within the tank extinguished.

All acuity tests were performed at a distance of 16 feet both in and out of the water. Four pairs of target sets were used, consisting of Landolt rings of various sizes and with gap orientation randomized in four positions. Each pair of target sets covered a different acuity range. Range 1 was from 16/64 to 16/178, Range 2 16/32 to 16/64, Range 3 16/16 to 16/32, and Range 4 16/9.6 to 16/19.2. The black Landolt rings on a white matte finish had been reproduced photographically resulting in size accuracy and high contrast between target and background.

A water and pressure-proof self-luminous target mount was used. It was equipped with a daylight-type fluorescent lamp of 20 watts power which was a few centimeters longer than the mounted targets. The lamp had a highly reflective metal cover placed so that almost all of the illumination was directed towards the targets. This arrangement

resulted in an average target luminance of 84 foot lamberts. The outer surface of the lamp cover and all other exterior parts facing towards the observer were painted black.

The target mount was equipped with a suspending line and support so that it could be lowered into the water after a target change. The targets were placed three feet beneath the surface when underwater tests were made.

Twenty subjects were used, with an age range of 20 to 43 years. It was first intended to use only qualified Navy divers but none were found with a monocular acuity poorer than 20/40 at 20 feet as measured with the Snellen Chart. Most had 20/20 or 20/15 visual acuity each eye. Since a spectrum of acuities seemed desirable, several non-diver subjects having distance acuities ranging to 20/200 were included.

SCUBA masks were worn during all visual acuity testing, both above and below the water surface. The face plate consisted of a single large plano lens. Care was taken to fit each subject with a mask that was comfortable and water-tight. Some difficulty was experienced in keeping the lenses free of fog, and tests were interrupted when necessary to clear them.

Prior to running tests a sensitive waterproofed light meter was used to take readings of the light reflected from the illuminated targets as measured from a distance of 16 feet, both above and below the surface. The per cent attenuation along the water path was then computed and compensated for during the surface visual acuity tests by interposing neutral filters of the appropriate density. In this way, target luminance was equated above and below the surface.

Pupil size measurements were not made. It was assumed that the controls in effect for luminance levels at the entrance pupils would result in negligible pupil size variations.

Each subject's visual acuity was first determined with a Snellen Chart in order to select the correct target size range for the tests. A test consisted of presenting five different sized Landolt rings, four times each, in random order of size and gap orientation. Targets were observed both monocularly (right and left eye) and binocularly.

Subjects were required to indicate the gap orientation of all rings that they could see well enough to make a judgment. During underwater testing a system of hand signals was used. The frequency of seeing for each target size was computed and the results were plotted on cumulative normal frequency of distribution graph paper. Acuity comparisons were made at the abscissa value (target size) of the 50% frequency of

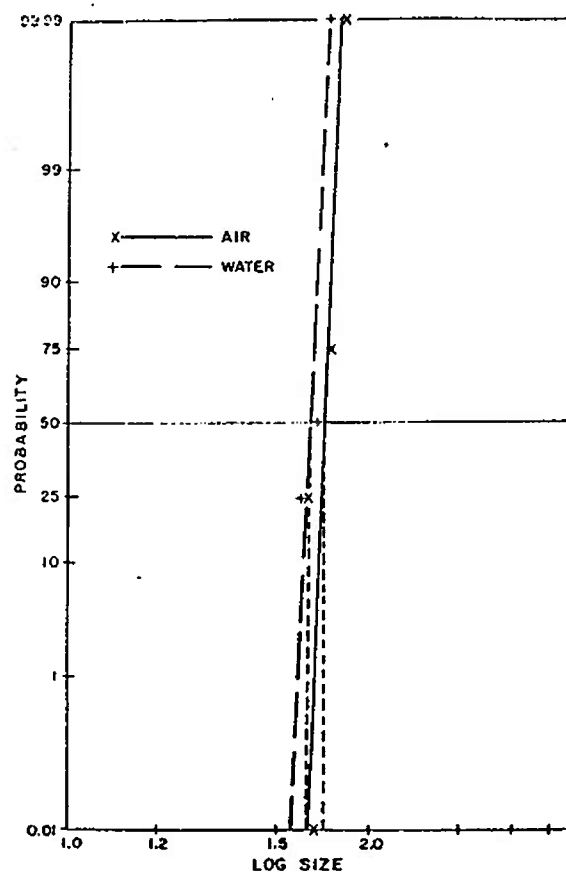


Fig. 3. Plot of the air and underwater visual resolution of Landolt Ring targets for one subject. The abscissa unit is the logarithm of the Snellen fraction denominator.

seeing intercept. This method results in a precise value for the denominator of the Snellen fraction (see Figure 3). The advantages and rationale of this method have been pointed out by Prince and Fry².

One purpose of these studies was to relate underwater acuity to operational situations where SCUBA or hard hat gear is worn. A certain amount of lens fogging must be accepted under these circumstances. In an attempt to compare surface and underwater acuities under more nearly optimum conditions, a waterproofed periscope was designed for below the surface viewing. The two subjects used in this experiment observed the targets monocularly through the periscope from a surface position. The targets were set at a distance of 16 feet from the observer, both above and three feet below the water surface. During underwater

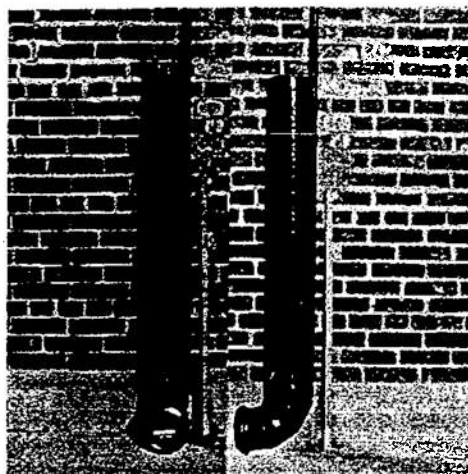


Fig. 4. Side and front views of periscope. A 45-degree mirror was situated at the bend. testing the objective of the periscope was placed at the same depth as the targets. The periscope is shown in Figure 4.

The right and left eye acuities of both subjects were correctable to 20/20. Various amounts of myopia were simulated by adding plus spheres to the full distance lens Rx.

RESULTS

Comparative visibility of the Landolt Ring targets in air and underwater at the same physical distance, with the SCUBA mask, is shown in Table 1 and Figure 5.

The means and medians indicate that smaller size test targets were seen underwater, both binocularly and monocularly. Binocularly, eleven of twenty subjects saw smaller sized targets underwater than in air at the same physical distance. Of the remainder seven tested the same above and below the water surface, and two saw better in air. Twenty-four of forty monocular determinations showed increased visibility underwater. There were twelve equalities and four reversals, two each for right and left eyes.

Since sample data did not suggest that a normal parent distribution would be assumed, a non-parametric statistic (Wilcoxon signed rank test)³ was used to test the null hypothesis that Landolt Ring size discrimination is no different in water than in air when targets are at the same physical distance. This probability was found to be less than 0.005 binocularly, 0.03 right eye, and 0.006 left eye. There is sufficient reason, therefore, for rejecting this hypothesis under all three viewing conditions.

TABLE 1

Resolution, in minutes of arc, of Landolt Ring targets 16 feet distant in air and in water. Criterion was 50% frequency of seeing. A SCUBA mask was worn for both underwater and surface testing. Twenty subjects.

0	—Binocular—		—Right—		—Left—	
	Air	Water	Air	Water	Air	Water
1	0.62	0.62	1.00	1.02	1.07	1.00
2	0.60	0.56	0.61	0.60	0.87	0.56
3	0.60	0.60	0.68	0.68	0.60	0.60
4	1.37	1.90	1.63	2.04	2.50	2.29
5	1.00	0.74	1.58	0.93	0.75	0.70
6	1.40	1.10	1.02	1.00	1.25	1.08
7	0.60	0.60	0.60	0.60	0.60	0.60
8	1.25	1.00	1.63	1.29	1.33	1.00
9	3.08	1.90	3.80	2.04	2.88	2.23
10	4.56	6.65	6.91	4.77	3.80	5.00
11	2.56	2.12	3.46	2.24	3.21	2.19
12	0.83	0.75	0.97	0.60	0.87	0.83
13	0.56	0.56	0.59	0.59	0.59	0.60
14	1.35	1.00	1.20	1.20	1.00	1.00
15	7.50	6.50	9.55	8.30	11.15	10.45
16	4.00	2.65	5.25	5.20	4.00	2.34
17	0.60	0.60	0.60	0.60	0.60	0.60
18	2.24	2.00	3.08	2.35	2.75	2.40
19	0.56	0.56	0.56	0.56	0.56	0.56
20	0.56	0.56	0.56	0.56	0.91	0.62
Σ	35.84	32.98	45.29	37.17	41.30	36.65
\bar{x}	1.79	1.65	2.26	1.86	2.07	1.83
Mdn.	1.12	0.87	1.11	1.01	1.04	1.00

Figure 6 was taken with a waterproof camera in an attempt to show the appearance of the target above and below water with the focal plane of the camera set at the image distance in water.

Target discrimination through the periscope was better underwater for all degrees of induced blur tested, as shown in Table 2 and Figure 7. There were no reversals or equalities. Mean and median target sizes were both smaller underwater.

SIZE AND DISTANCE JUDGMENTS

This experiment was performed by Luria, Kinney, and Weissman⁴ in a fresh water lake. The lake was equipped with a below surface room fitted with a viewing port and target track for underwater research.

Size judgments were made using a 4-inch square white test target, and white comparison targets in a range of sizes. Comparisons were made one at a time in a random order both in air and while the test target occupied one of two positions on the underwater track.

Two groups were tested: one consisted of 20 randomly selected vacationers and the other of six experienced divers.

Size Estimations: Sizes were estimated as greater in water for both distances tested and by both groups.

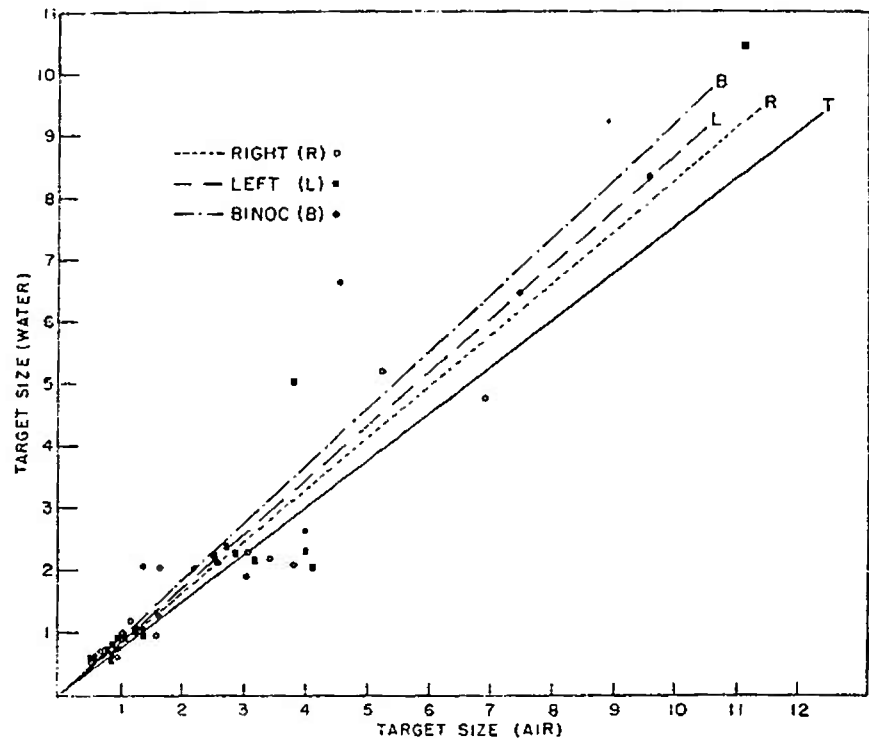


Fig. 5. Scattergram, with fitted least squares lines, of the coordinates for air and water viewing of Landolt Ring targets through a SCUBA mask. Data for right (R), left (L) and binocular (B) vision of twenty subjects. Line T conforms to the theoretically expected relationship. Criterion was 50% frequency of resolution of the gaps in the rings. Target size is noted as the angular subtense of the ring gaps, in minutes of arc, at the nodal point.

Distance Estimation: The task was to estimate the relative distance of a standard and a variable distance target. Comparisons were made while the variable target was observed both in air and on the underwater track. Subjects were from the same two groups used for size estimations.

Except at viewing distances of three feet or less the median estimates of distance by the randomly selected group was greater in water than in air. The diver's estimates showed little difference under the two conditions.

Both size and distance were increasingly overestimated underwater by the unselected group as the target was moved farther away. The diving group did not show this to the same extent.

COLOR VISION

TABLE 2

Resolution in minutes of arc of Landolt Ring targets 16 feet distant, seen through a periscope in air and in water. Criterion was 50% frequency of seeing. Myopia was simulated by making plus additions to the distance Rx. Combined data for two subjects.

0	Eye	+ add	Target Size	
			Surface (x_a)	Underwater (x_w)
1	R	1.50	10.25	6.65
"	R	1.00	4.40	4.00
"	R	0.75	2.70	2.35
"	R	0.25	1.35	1.10
"	R	0.00	1.10	0.95
2	L	1.50	6.30	5.65
"	R	1.50	8.00	4.65
"	R	0.50	2.45	2.18
			Σx_a 36.55	Σx_w 27.53
			\bar{x}_a 4.57	\bar{x}_w 3.44
			median (\bar{x}_a) 3.55	(\bar{x}_w) 3.17

The visibility of colors underwater varies with depth, illumination, transmission characteristics of the body of water and color of the object.

Kinney, *et al.*⁵ investigated the visibility of fluorescent paint in contrast to non-fluorescent paints at two depths, 3 and 33 feet in fresh water, and at various viewing distances. Observers wore SCUBA masks.

Ultraviolet penetrates poorly in water but paints are available which fluoresce in the presence of short wave length visible light. These paints were used in the study.

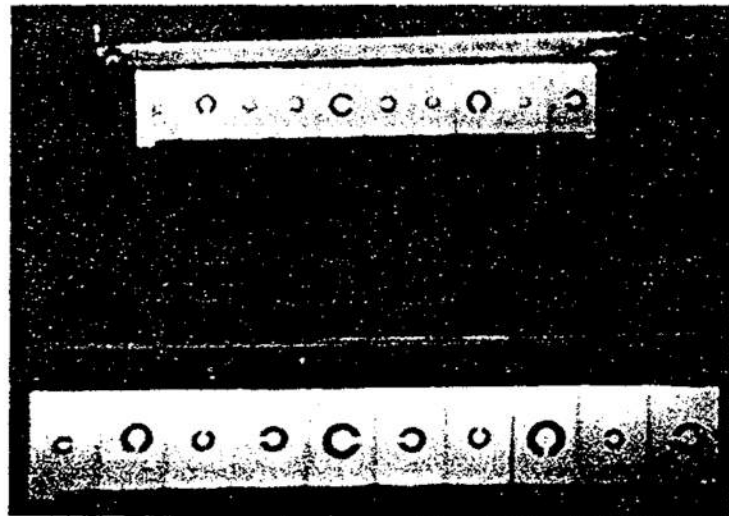


Fig. 6. Photographs of one of the test targets taken from a distance of 16 feet in air (above) and underwater (below). The camera was focused for 12 feet in both cases.

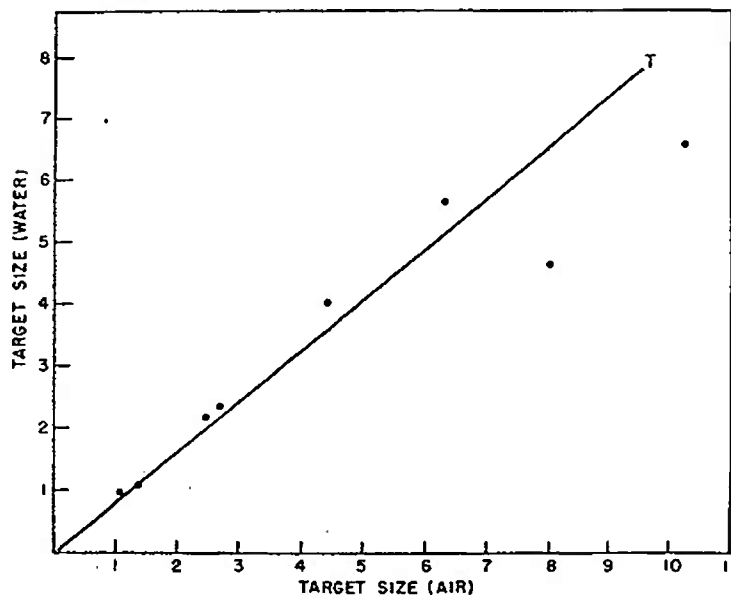


Fig. 7. Scattergram of the coordinates for air and water resolution, at the 50% frequency of seeing intercept, of Landolt Ring targets when viewed through a non-magnifying (1:1) periscope: combined data of right and left eyes of two subjects. Line T represents the predicted relationship. Myopia, of various degrees, was simulated by interposing plus spheres. Target size is noted as the angular subtense of the ring gaps, in minutes of arc, at the nodal point.

The results showed better visibility of fluorescent paints at both depths tested and at all viewing distances. The yellows, including greenish yellow and orange yellow were the most visible colors in the specific bodies of water where the tests were made.

DISCUSSION

The apparent displacement x , along the line of sight, of an object located in a homogeneous optical medium of refractive index n , when viewed normally to the plane of the interface from a second homogeneous optical medium of refractive index n' , is, for paraxial rays:

$$x = \frac{n - n'}{n} d$$
 where d is the distance from object to interface. For an ob-

ject in water, with the eye in air, the displacement varies slightly with water temperature. For water at 92° Fahrenheit, and $d = 16$ feet,

$$x = \frac{1.331 - 1.00}{1.331} 16 = 3.98 \text{ feet.}$$
 An object at 16 feet would appear to be at 12.02 feet ($16 - 3.98$), if the observing eye is at, or very near, the interface.

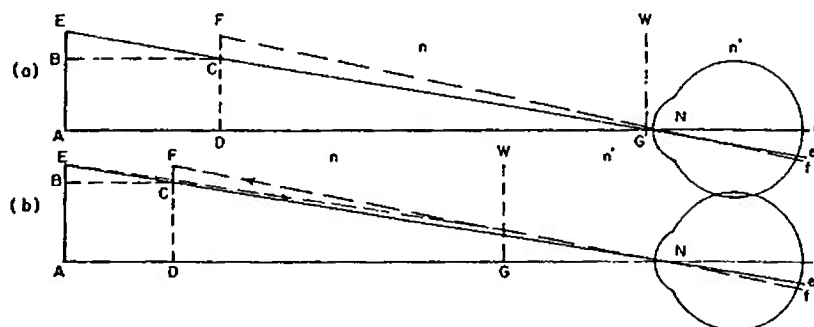


Fig. 8. (a), (b). Reduced eye schematic of object/retinal image relationship when the target ABE is viewed in air; and in water when its positively displaced image is shown as DCF. The retinal images are, respectively, *ae* and *af*. *N* is the nodal point. *WG* represents the air/glass/water interface (*s*) in two positions: Very close to the observing eye (a), and significantly distant from it (b).

Since the image of an underwater target is displaced towards the observer, it will also appear larger than if in air and the amount will be in proportion to the displacement, if the line of sight is normal to the interface. This is represented schematically in Figure 8 (a) (b) where *AD* is the positive displacement of the target *ABE* whose underwater image is *DCF*. Figure 8a is schematically similar to the case where the targets were viewed underwater through a SCUBA mask, with the air/glass/water interface (*s*) very near the observers' eye.

How much smaller can the target in water be whose image will subtend the same visual angle as another target observed in air at the same physical distance? Referring to Fig. 8a, the problem consists of determining the size of the target whose image, *DC*, subtends the same visual angle as target *ABE*. It can be computed as follows:

Let $y = AB + BE$, $x = CF$, $AB = DC$ and $CF = BE$, then $DC = y - x$ and $\frac{y}{AN} = \frac{y - x}{DN}$. If $AN = 16$ feet and $DN = 12$ feet, then by substitution:

$$\frac{y}{16} = \frac{y - x}{12} \quad 16x = 4y, \quad x = 0.25y$$

The linear dimension of the target *ABE*, as seen in air, may be reduced by an amount equal to the segment *BE*, or 25 per cent, when viewed underwater, and the subtended visual angles under the two conditions will be equal. A reduction of this order was reached, and even exceeded with some subjects, but in most cases the minimum target size resolved underwater was larger than theory would predict. This is illus-

trated in Figure 5. The slopes of the lines fitted to the data for binocular, right, and left eyes by the least squares method are all less than that of the line corresponding to theory, although a few paired air and water tests yielded coordinates below this line which would indicate an improvement in resolution underwater exceeding the predicted.

The results were affected by: (1) Lens fogging, which no doubt led to some of the reversals and (2) lack of sufficiently small targets for some observers who were able to discriminate the smallest targets presented, both in and out of water. It is reasonable to expect that if fogging had been better controlled and smaller target sizes provided the results would have more nearly approached the predicted.

Since the retinal image size difference for the two conditions is determined by the tangents of the angles subtended at the eye by the target in air and its positively shifted image in water, the difference will decrease with increasing distance from the air/water boundary (observer in air), when line of sight is normal to the interface. This was the case with the periscope, where 54.6 inches of the 16-foot light path from the target was through air within the instrument. Referring to Figure 8b, the increase in retinal image size, ef , is proportional to AD as before, but AD is now a smaller fraction of the dimension AN and, therefore, ef will be smaller also.

The target displacement in water at 92° would be:

$$AD = \frac{n - n'}{n} d, \text{ where } d = AG = 137.4 \text{ inches, } n = 1.331, \text{ and } n' = 1.00$$

Substituting, $AD = \frac{1.331 - 1.00}{1.331} 137.4 = 34.2$ inches. Since $GN = 54.6$ inches, the target distance in air is $137.4 + 54.6 = 192$ inches, or 16 feet, and its image would be $137.4 - 34.2 + 54.6 = 157.8$ inches, or 13.15 feet distant in water.

The theoretically expected reduction in target size underwater can be computed as before. Let $CF = x$, $AB + BE = y$, and $DC = y - x$, then $\frac{y}{AN} = \frac{y - x}{DN}$. Since $AN = 16$ feet and $DN = 13.15$ feet, then

$$\text{by substitution } \frac{y}{16} = \frac{y - x}{13.15}, 16x = 2.85y, x = 0.18y.$$

The linear dimension of the target ABE , as seen in air, may be reduced by an amount equal to the segment BE , or 18 per cent, for equal angular subtense in water. The scatter-plot (Figure 5) shows that

most experimental values were reasonably close to those theoretically predicted, except for two tests, when resolution underwater substantially exceeded the predicted.

SUMMARY

Experiments were performed at the Naval Submarine Medical Center comparing visual resolution, and size and distance judgments underwater, with the same measures in air. The underwater visibility of fluorescent vs. non-fluorescent pigments was also investigated.

Under the experimental conditions it was found that: 1. At short range, visual resolution of a target in water was better than in air at the same physical distance; 2. except at short ranges, both size and distance were overestimated underwater compared to air viewing; 3. fluorescent pigments were found to be more visible underwater than non-fluorescent types.

ACKNOWLEDGMENTS: R. Hester, Ph.D., rendered valuable assistance in the statistical treatment of the data. Thanks are also due Lt. Gordon L. Barclay, Director, Escape Training Tank, for his cooperation, and to the subjects, all of whom were volunteers.

(The opinions or assertions contained herein are the private ones of the author and are not to be construed as official or reflecting the views of the Navy Department or Naval Service at large.)

REFERENCES

1. Kent, P. R., and S. Weissman, Visual Resolution Underwater. Groton, Conn., Naval Submarine Medical Center, Apr., 1966. Report No. 476.
2. Prince, Jack H., and Glenn A. Fry, The effect of errors of refraction on visual acuity, *Am. J. Optom. and Arch. Am. Acad. Optom.* 33 (7): 353-373, 1956.
3. Dixon, Wilfrid J., and Frank J. Massey, Jr., *Introduction to Statistical Analysis*, 2d ed. New York, McGraw-Hill Book Co., 1957, p. 488.
4. Luria, S. M., Jo Ann S. Kinney, and S. Weissman, Estimation of size and distance underwater. Groton, Conn., Naval Submarine Medical Center, Dec. 10, 1965. Report No. 462.
5. Kinney, Jo Ann S., S. M. Luria, S. Weissman, and H. H. Matteson, Underwater Visibility of Fluorescent and Non-Fluorescent Paints. Groton, Conn., Naval Submarine Medical Center, Sept. 1, 1965. Memo. Report No. 65-11.